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High-resolution observations of interstellar Na I towards HD 174632

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Summary. High resolution observations of interstellar Na I towards the relatively nearby (180 pc) and lightly reddened [$E(B-V)=0.12$] B8V star HD 174632 are presented. There are two distinct interstellar cloud components in this line-of-sight, with heliocentric velocities of about -4.4 and $-17.6\,\mathrm{km\,s^{-1}}$. A third, much weaker, component at about $-21.7\,\mathrm{km\,s^{-1}}$ also appears to be present. Na I column densities for these components have been obtained by line-profile fitting, and estimates have been made of the N(Na I)/N(H) ratios. These are found to be consistent with standard diffuse interstellar clouds. Arguments are presented that these clouds are associated with the boundary between the local low-density interstellar bubble and the neighbouring Loop I bubble, at a distance between about 50 and 100 pc from the Sun.

1 Introduction

This paper reports the serendipitous discovery of an interesting interstellar sightline, made during the course of a more extensive programme of high-resolution interstellar spectroscopy using the coudé échelle spectrograph of the Mt Stromlo 74-inch telescope. The target was HD 174632 ($l=5\overset{\circ}{.}2$, $b=13\overset{\circ}{.}7$, $V=6.6$) and was observed originally as one of several lightly-reddened late B stars in an attempt to determine the likely importance of stellar Na I for the measurement of the interstellar line towards similar stars. In the event, the spectrum was found to be dominated by strong interstellar lines. There was no sign of stellar Na I. There are, to the author's knowledge, no other observations of the interstellar spectrum of this star in the literature.

Garrison, Hiltner & Schild (1977) give the spectral type of HD 174632 as B8*V*, which, combined with the intrinsic colours of Deutschman, Davis & Schild (1976) and photometry of Schild, Garrison & Hiltner (1983), gives a reddening of $E(B-V)=0.12$ and a distance (assuming $R=3.1$) of 180 pc.

2 Observations

The observation of HD 174632 was obtained on 1987 June 14 at approximately 21:00 UT. The exposure time was 2500 s. The spectrograph was used with the 130-inch camera, giving a dispersion at Na D_2 (5889.950 Å) of 0.53 Å mm^{-1}. The slit width was 250 μm, providing a velocity resolution (FWHM) of 3 km s^{-1}. A more detailed discussion of the instrumental characteristics of this spectrograph has been given by Crawford, Rees & Diego (1987). The detector was a Photon Counting Arrray (PCA, Stapinski, Rodgers & Ellis 1981) which has a spectral coverage of about 6 Å at Na D. Wavelength calibration was provided by a thorium–argon lamp, although only two lines from the lamp were found to lie within the 6 Å covered by the detector, and it was necessary to linearly interpolate between them. Calculations based on the theoretical dispersion of the instrument indicate that the maximum error introduced by this approximation will amount to $\pm$5 mÅ (0.3 km s^{-1}), although this does not allow for any distortions due to the detector itself.

The PCA image was divided by a flat field and the background, obtained from either side of the spectrum, was subtracted. The spectrum was extracted using the FIGARO program (due to K. Shortridge and described by Bridger 1987) on the UCL STARLINK node, rectified, and a heliocentric correction applied to the wavelength scale.

Weak atmospheric (mostly water) lines occur in this part of the spectrum (see, for example, Hobbs 1978). For the particular region of the spectrum discussed here, two lines are important: a water line at 5889.637 Å (Moore, Minnaert & Houtgast 1966), and a line at about 5890.09 Å (not identified as water, see fig. 1 of Hobbs 1978). These correspond to heliocentric velocities of -7.2 and $+15.9$ km s^{-1}, respectively (relative to the D_2 line). Both of these lines reach a relative intensity of about 0.8 (i.e. they are about 20 per cent deep). They were removed by dividing by a *mean* atmospheric spectrum, obtained by merging spectra of unreddened early-type stars with no sign of either stellar or interstellar Na I. These unreddened spectra were obtained by Drs M. J. Barlow and J. C. Blades with the same instrument in 1979. Although atmospheric lines can be highly variable, inspection of the result (see below) shows that λ5890.09, which is clear of the interstellar absorption, has been successfully removed. This gives us confidence that the other line, which is hidden by one of the interstellar components, has been properly allowed for. In any case, the effect on the profile of the interstellar component by this procedure was found to be negligible.

The spectrum of interstellar Na D_2 is shown in Fig. 1, from which it is clear that there are two distinct, sharp, and almost equally strong, absorption components with heliocentric velocities of about -17.6 and -4.4 km s^{-1}. Closer inspection reveals the probable presence of another,

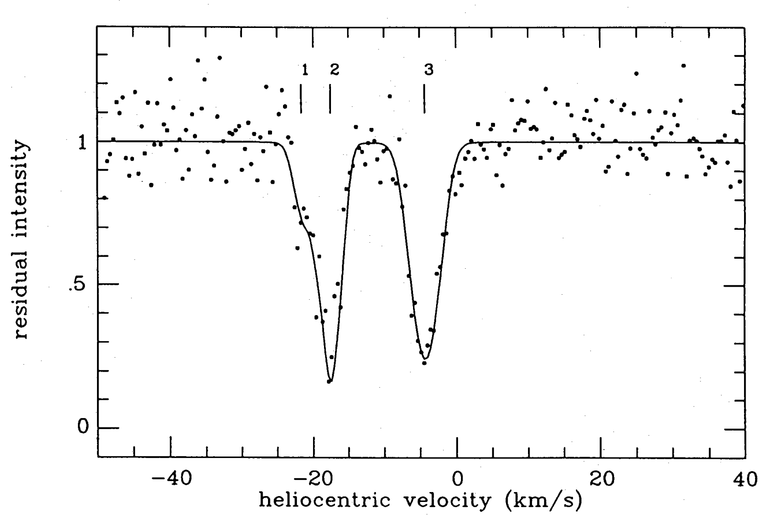

Figure 1. The spectrum of interstellar Na I towards HD 174632. The dots are the observed intensities. The solid line is a model with the parameters given in Table 1.

weaker, component blended with the blue wing of the $-17.6\,\mathrm{km\,s^{-1}}$ component. The total equivalent width of the whole feature (all three components) is 155 ± 12 mÅ.

3 Line profile analysis

In order to obtain accurate column densities for these components (which do not lie on the linear part of the curve of growth) and to determine their velocity dispersions, theoretical line profiles were calculated using the BACH program, due originally to Davenhall (1977), on STARLINK. Each cloud component is described by a radial velocity, v, column density, N, and velocity dispersion parameter, b. The Na D lines are subject to hyperfine splitting (e.g. Blades, Wynne-Jones & Wayte 1980) and this must be allowed for in the analysis. For the D_2 line the splitting amounts to $0.97\,\mathrm{km\,s^{-1}}$, which, although below the resolution of the present study, was found to broaden the profiles. It was accounted for by performing the line profile calculation for each hyperfine component separately and then blending them together. The oscillator strength of the transition was taken to be 0.650 and was scaled by the ratios of the statistical weights to get the relative strengths of the hyperfine components (Blades, Wynne-Jones & Wayte, 1980).

The theoretical line profiles were convolved with the instrumental response function (IRF) to enable comparison with the observations. Here the IRF has been taken from Crawford *et al.* (1987). The parameters b and N were varied for each component until a satisfactory fit to the data was obtained. It is not possible to obtain a unique solution for b and N, but it is possible to determine their possible range for each component. Fig. 1 shows such a model superimposed on the observed spectrum. The parameters chosen for this model, and their permitted range, are given in Table 1.

Table 1. Model parameters for the theoretical line profiles shown in Fig. 1. Powers of 10 are given in parentheses. Δb and ΔN are the permitted ranges of b and N. The maximum column density for component 2 could be considerably higher than given here if $b\leqslant0.8\,\mathrm{km\,s^{-1}}$ (see text).

Comp. no.	v $\mathrm{km\,s^{-1}}$	b $\mathrm{km\,s^{-1}}$	Δb $\mathrm{km\,s^{-1}}$	N $\mathrm{cm^{-2}}$	ΔN $\mathrm{cm^{-2}}$
1	−21.7	1.0	⩽2.0	1.1 (11)	0.8–1.4 (11)
2	−17.6	1.0	⩽1.2	7.5 (11)	6.0–9.0 (11)
3	−4.4	2.0	1.5–2.5	6.5 (11)	5.5–7.5 (11)

The b value for the $-21.7\,\mathrm{km\,s^{-1}}$ component is not well constrained because of blending with the stronger component at $-17.6\,\mathrm{km\,s^{-1}}$, and it was only possible to obtain an upper limit. An upper limit to b is also given for the $-17.6\,\mathrm{km\,s^{-1}}$ component, but for a different reason: because of the convolution with the IRF, the models become insensitive to b values significantly smaller than the IRF. In practice it was found that the analysis was incapable of distinguishing between b values $\leqslant0.8\,\mathrm{km\,s^{-1}}$, and that a model with this b value gave a satisfactory fit to the $-17.6\,\mathrm{km\,s^{-1}}$ component. It was therefore not possible to determine a lower limit to the b value. This also makes the upper limit to the column density somewhat uncertain. The value given in Table 1 corresponds to the case where $b=0.8\,\mathrm{km\,s^{-1}}$. Smaller values of b would result in larger N values. For $b=0.3\,\mathrm{km\,s^{-1}}$, for example, $N\geqslant10^{13}$ is allowed.

The b value is a measure of both the thermal velocities in an interstellar cloud and any turbulent motions that may be present. We have:

$$b=\left(\frac{2kT}{m}+2v_{\mathrm{t}}^{2}\right)^{1/2}$$

where v_t is the rms turbulent velocity along the line-of-sight, k is Boltzmann's constant, T is the kinetic temperature, and m is the mass of the atom or ion observed. Because there is no independent way to determine the degree of turbulence within the material, this equation can only be used to determine an upper limit to the kinetic temperature. In the absence of turbulence (v_t=0) we have (for Na):

$$b=0.268\,(T/100\,\mathrm{K})^{1/2}\,\mathrm{km\,s^{-1}}.$$

Taking the upper limits to the b values given in Table 1, we get upper limits for the temperature of 5600, 2000 and 8700 K for the −21.7, −17.6 and −4.4 km s^{-1} components, respectively. The −4.4 km s^{-1} component also has a lower limit (in the absence of turbulence) of 3100 K.

The typical kinetic temperature of interstellar diffuse clouds is generally taken to be about 80 K, from observations of rotational excitation of molecular hydrogen (e.g. Savage *et al.* 1977). This corresponds to a b value for Na of only 0.24 km s^{-1}. Although the −17.6 km s^{-1} component, because of the resolution constraint discussed above, could be consistent with this low b value (as could the −21.7 km s^{-1} component, in principle, but this is poorly constrained) the −4.4 km s^{-1} component is not. If we *assume* a kinetic temperature of 80 K, we derive upper limits to v_t of 1.40, 0.83 and 1.76 km s^{-1} for the three components. The corresponding lower limit of the −4.4 km s^{-1} component is 1.04 km s^{-1}. The sound speed for diffuse interstellar clouds is about 0.7 km s^{-1} (Spitzer 1978). Thus while the −17.6 km s^{-1} component (and possibly the −21.7 km s^{-1} component) is consistent with diffuse cloud temperatures and subsonic turbulent velocities, the −4.4 km s^{-1} component (if truly a single component) is either significantly hotter than a standard diffuse cloud, or is subject to supersonic turbulent motions.

4 Estimates of the N(Na I)/N(H) ratios

There has been no accurate determination of the hydrogen column density for this star. Using the empirical relation of Bohlin, Savage & Drake (1978), $N(\mathrm{H\,I}+\mathrm{H_2})/E(B-V)=5.8\times10^{21}\,\mathrm{cm^{-2}\,mag^{-1}}$, gives an estimated hydrogen column density of $7\times10^{20}\,\mathrm{cm^{-2}}$. If we make the assumption that all the hydrogen exists in the three identified velocity components, and is shared between them in the same proportions as the Na I, then the lower limits to the Na I column densities given in Table 1 can be used to obtain a lower limit to the N(Na I)/N(H) ratio of 1.8×10^{-9} for each component. Bohlin *et al.* found that deviations from their empirical relation were generally less than a factor of 1.5. If we assume that the hydrogen column density has been underestimated by a factor 1.5 for this star, then the above lower limit to the N(Na I)/N(H) ratio falls only slightly, to 1.2×10^{-9}.

The N(Na I)/N(H) ratio is given (e.g. Hobbs 1978) by:

$$N(\mathrm{Na\,I})/N(\mathrm{H})\sim n_e A\,\alpha(T)/\Gamma$$

where A is the fractional abundance of sodium, n_e is the electron number density, $\alpha(T)$ is the radiative recombination coefficient for Na II, and Γ is the photoionization coefficient for Na I.

Hobbs identified a $N(\mathrm{Na\,I})/N(\mathrm{H})\gtrsim1\times10^{-9}$ to be characteristic of standard diffuse interstellar clouds ($n_\mathrm{H}\sim$few tens cm^{-3}, $T\sim$80 K). A less dense and/or hotter material has a smaller N(Na I)/N(H) ratio because of a lower n_e and because $\alpha(T)$ decreases with increasing temperature. In this respect, it is interesting to note that, using Seaton's (1951) recombination coefficients, a temperature of 2000 K would reduce the N(Na I)/N(H) ratio by a factor of 10 from its value at 80 K for a gas at the same density. The relatively large values estimated for this ratio from the observations therefore suggest that the observed breadth of the −4.4 km s^{-1} component is due to turbulence (or an unresolved blend) rather than to an anomalously high temperature.

5 Discussion

Taking Oort's constant, A, to be $14.4\,\mathrm{km\,s^{-1}\,kpc^{-1}}$ (Kerr & Lynden-Bell 1980) indicates that a cloud partaking in the galactic rotation somewhere along the 180 pc line-of-sight to HD 174632 should occupy the very narrow LSR velocity range $0 \leqslant v_{\mathrm{LSR}} \leqslant 0.5\,\mathrm{km\,s^{-1}}$. For this particular line-of-sight, heliocentric velocities are $9.4\,\mathrm{km\,s^{-1}}$ more negative than LSR values, so this corresponds $-9.4 \leqslant v_{\mathrm{helio}} \leqslant -8.9\,\mathrm{km\,s^{-1}}$. None of the observed velocity components occupy this velocity range and it is clear that they have peculiar motions unrelated to galactic rotation HD 174632 itself has a radial velocity of $-50\,\mathrm{km\,s^{-1}}$ (Hoffleit & Jaschek 1982), and so it is unlikely that any of the material is associated with the star: any material lost by the star would be seen at an even more negative velocity.

HD 174632 lies in a direction, and at a distance, such that the line-of-sight ought to pass through a relatively empty part of the interstellar medium. There is considerable evidence (see Cox & Reynolds 1987, for a recent review) that the Sun lies in an irregularly shaped, low-density ($n_{\mathrm{H}} \sim 5 \times 10^{-3}\,\mathrm{cm^{-3}}$) bubble in the interstellar medium. The local bubble is thought to be largely (and perhaps completely) free of standard (as defined above) diffuse interstellar clouds, although 'wisps' of lower density material may exist. In the direction to HD 174632 the local bubble extends for about 50–100 pc, where it is bounded by a 'wall' of neutral hydrogen that has been swept up by a larger (diameter about 300 pc), expanding bubble associated with the Loop I radio feature and centred on the Sco–Cen association about 200 pc from the Sun. [Loop I, also known as the North Galactic Spur, was postulated to be a supernova remnant by Hanbury Brown, Davis & Hazard (1960), although consideration of both the radio and X-ray data suggests that a single supernova remnant cannot be responsible (Iwan 1980).] The properties of the interior of the Loop I bubble are thought to be similar to those of the local bubble. Paresce (1984) identified the boundary wall as occupying the longitude range $270° \lesssim l \lesssim 15°$, and there is evidence that the wall is thicker at negative galactic latitudes (Cox & Reynolds 1987, and references therein). A distance of 180 pc would place HD 174632 within the Loop I bubble, and it therefore makes sense to suppose that

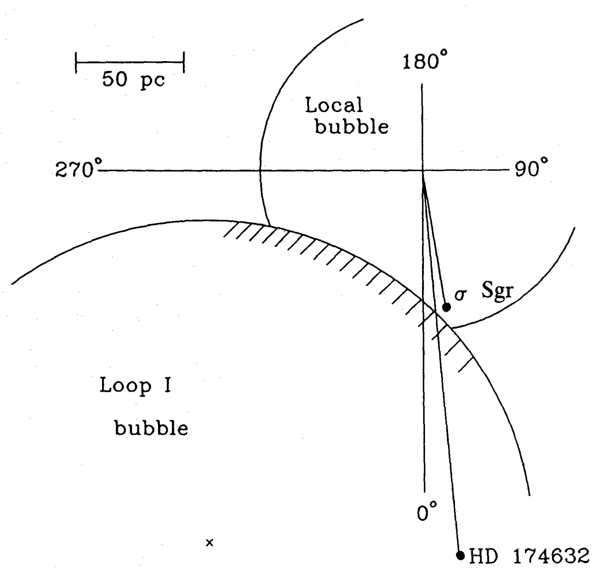

Figure 2. Schematic representation of the positions of HD 174632 and σ Sgr, projected on to the galactic plane, relative to the Loop I and local bubbles. The approximate location of the wall separating the two bubbles, the proposed location for the clouds observed here, is indicated by hatching. Galactic longitudes are marked running anticlockwise about the solar position. The estimated centre of the Loop I bubble ($l \sim 330°$, $b \sim +24°$ is indicated by a cross. The reader is referred to the review by Cox & Reynolds (1987) for a full discussion of the structure of the local interstellar medium.

the absorption features are associated with the wall separating the two lower-density regions. Fig. 2 shows a schematic representation of the proposed geometry.

Hobbs (1978) failed to detect Na I towards the star σ Sgr which lies at a distance of about 65 ± 20 pc (Paresce 1984, and references therein) in a similar direction ($l=9\overset{\circ}{.}6$, $b=-12\overset{\circ}{.}4$) to HD 174632 (Fig. 2). This is consistent with σ Sgr being within the local bubble but very close to the boundary. At a distance of 65 pc the separation of the two lines-of-sight is only 5 pc, and the non-detection of Na I towards σ Sgr strongly supports the view that the clouds observed towards HD 174632 occur outside the local bubble, and are most likely associated with the 'wall' of neutral gas at the boundary. If so, it follows that the 'wall', at least in this direction, consists of discrete clouds (or sheets) with characteristics broadly similar to those of standard diffuse interstellar clouds.

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